

21cm Epoch of Reionization Measurements

D. C. Backer, UC Berkeley

1. Global Spectrum (a la Penzias & Wilson CMB)

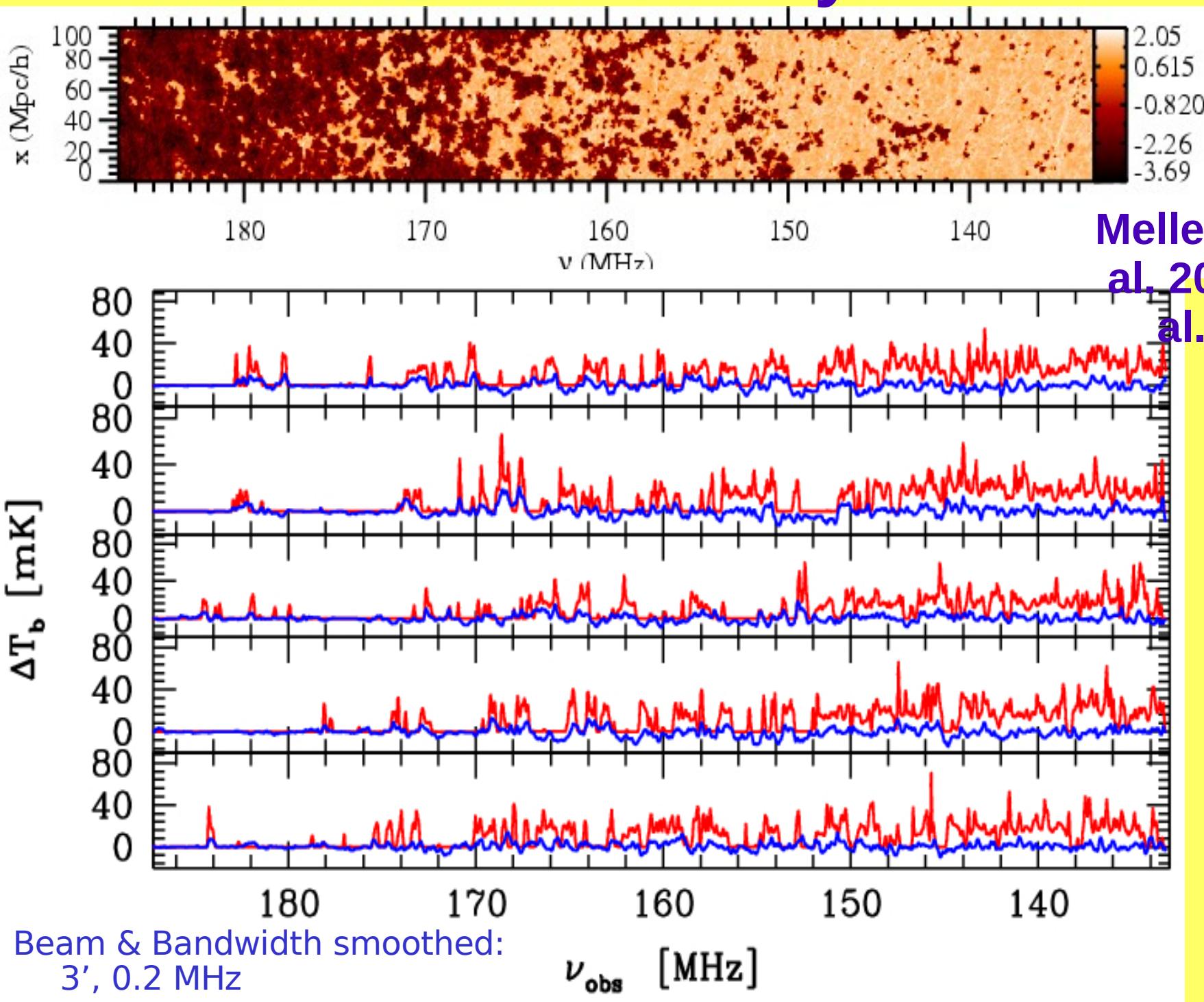
- 1.1. CoRE – Ekers, Subrahmanian, Chippendale
- 1.2. EDGES – Rogers, Bowman

2. Stochastic Power Spectrum (a la COBE CMB)

- 2.1. PAST/21CMA – Wu, Petersen, Pen, et al.
- 2.2. LOFAR – de Bruyn, Brentjen, et al.
- 2.3. PAPER – Backer, Bradley, Parsons, et al.
- 2.4. GMRT – Pen, Petersen, et al.
- 2.5. MWA – Lonsdale, Whitney, Greenhill, et al.

3. Image Structures for Evolution & Cosmology (a la WMAP/Planck): SKA

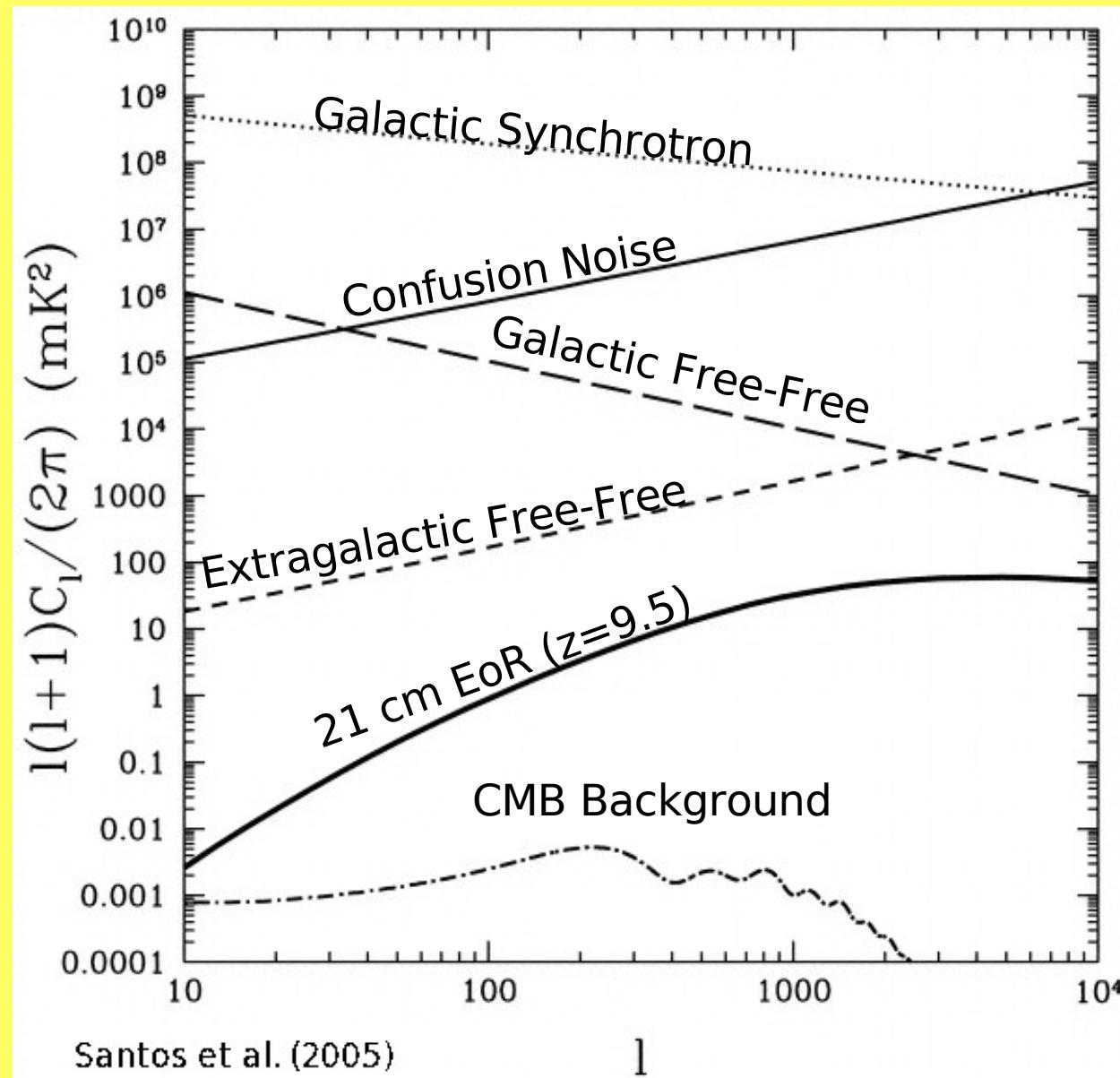
Simulations of Early Universe



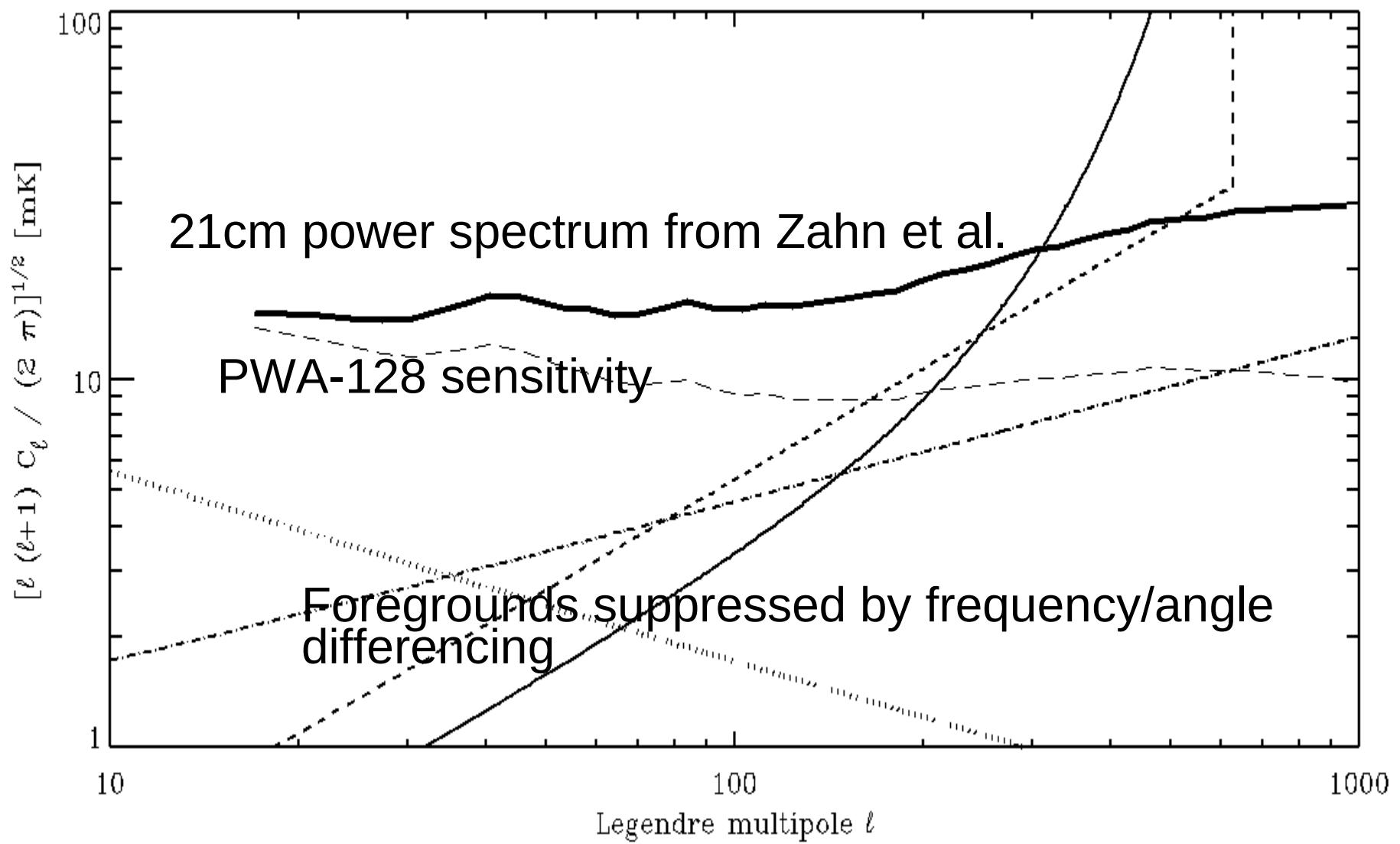
Foregrounds, and Other Challenges

"If it were easy, it would have been done already"

- Discrete sources: galaxy; sun
- Confusion noise
- Polarized galactic synchrotron
- Free-free emission
- Ionosphere: refraction, scintillation
- Hardware stability
- Ultra-wide field imaging



Power Spectrum of 21cm Fluctuations

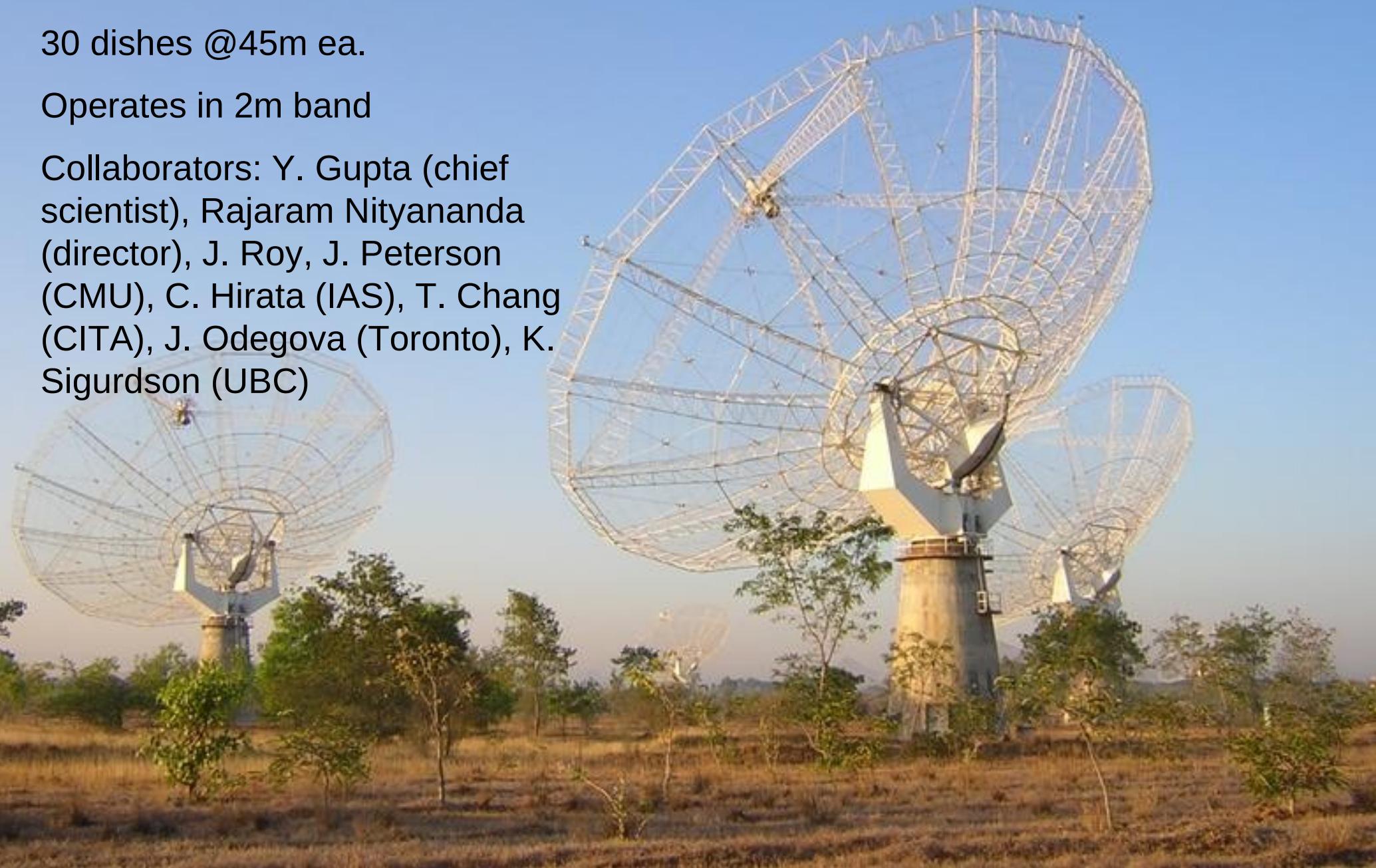


Giant Meterwave Radio Telescope in India

30 dishes @45m ea.

Operates in 2m band

Collaborators: Y. Gupta (chief scientist), Rajaram Nityananda (director), J. Roy, J. Peterson (CMU), C. Hirata (IAS), T. Chang (CITA), J. Odegova (Toronto), K. Sigurdson (UBC)



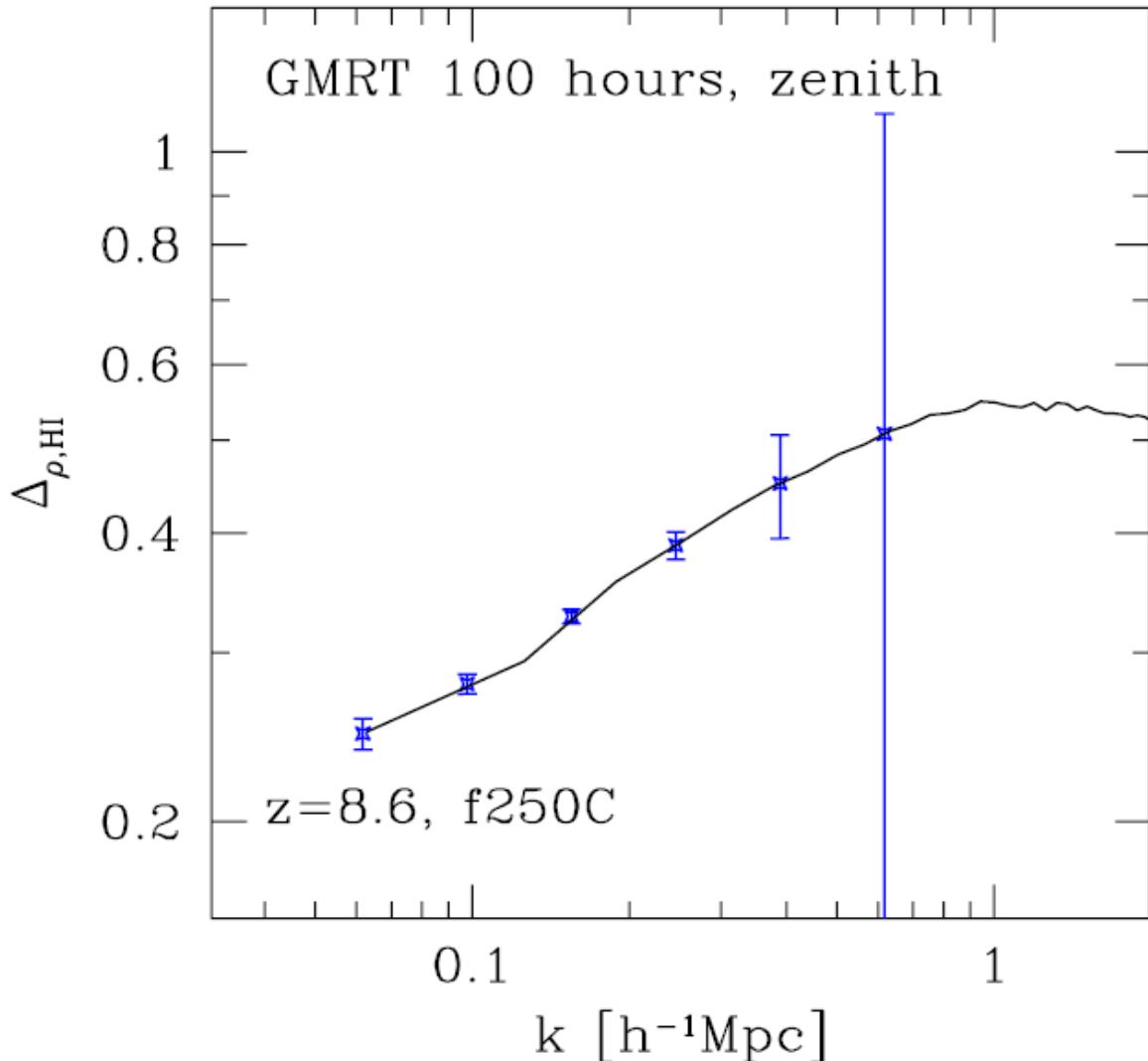
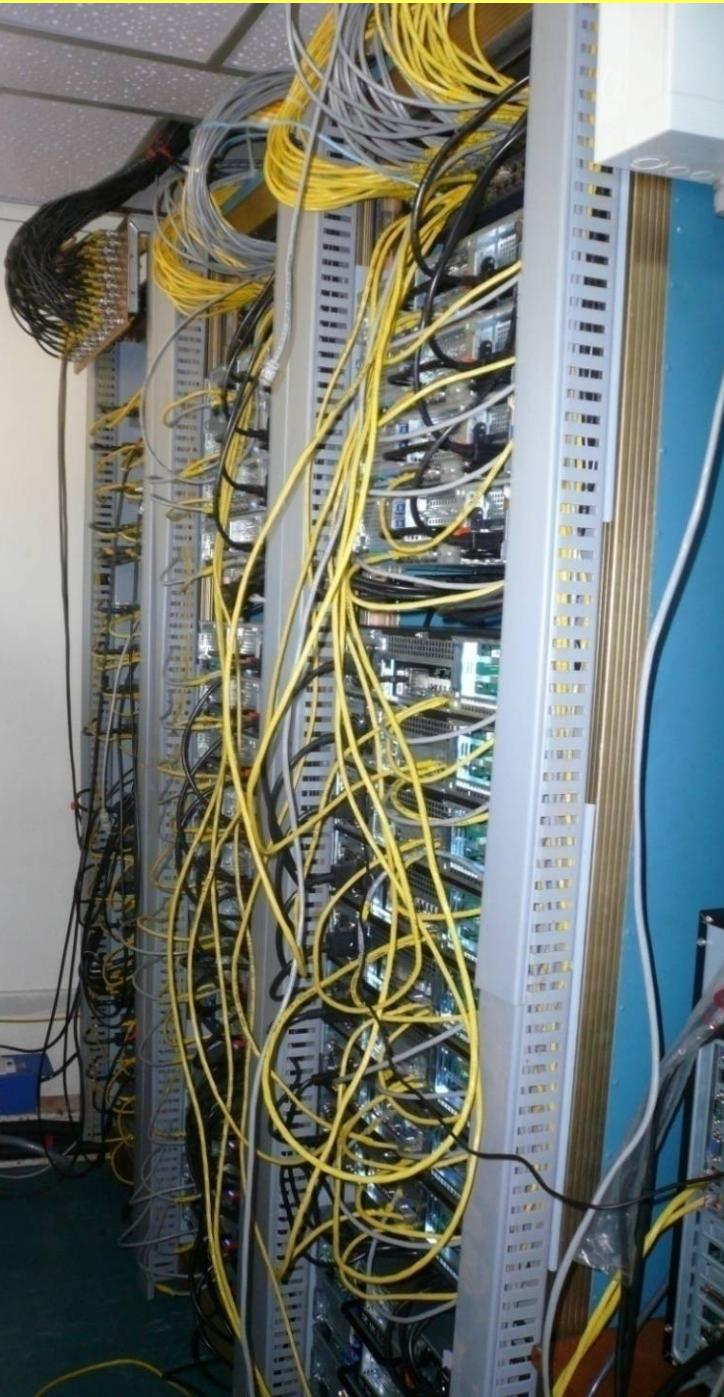


Figure 9. Observability of the 21-cm signal: the 3D power spectrum of the neutral hydrogen density, $\Delta_{\rho, HI}$, at redshift $z = 8.59$ ($\bar{T}_b = 16.3$ mK) with the forecast error bars for 100 hours observation with GMRT vs. wavenumber k . We assumed 15 MHz observing bandwidth (the full instantaneous bandwidth of GMRT), $T_{\text{sys}} = 480$ K and assuming $T_S \gg T_{\text{CMB}}$. The array configuration is assumed pointed to the zenith, but the sensitivity is only weakly dependent on the pointing.

new software correlator: imaging the full sky to horizon





PAPER: PRECISION ARRAY TO PROBE THE EPOCH OF REIONIZATION

PAPER Team: R. Bradley (Co PI), E. Mastrantonio, C. Parashare, N. Gugliucci, D. Boyd, P. Reis (NRAO & UVA); A. Parsons, M. Wright, D. Werthimer, G. Foster, CASPER group (UC Berkeley); D. Herne, M. Lynch (*Curtin Univ*); C. Carilli, A. Datta, A. Deller (NRAO Socorro); J. Aguirre, D. Jacobs (*Penn*)

Our experiment is working toward a detection of the power spectrum of brightness temperature structures of redshifted 21cm hydrogen line emission produced by the first stars.

Using a dipole array we will:

- (a) image the sky at many frequencies averaging over many months to achieve mK sensitivity;**
- (b) difference image in angle and in frequency (red shift or time);**
- (c) form a statistical summary to find signal.**

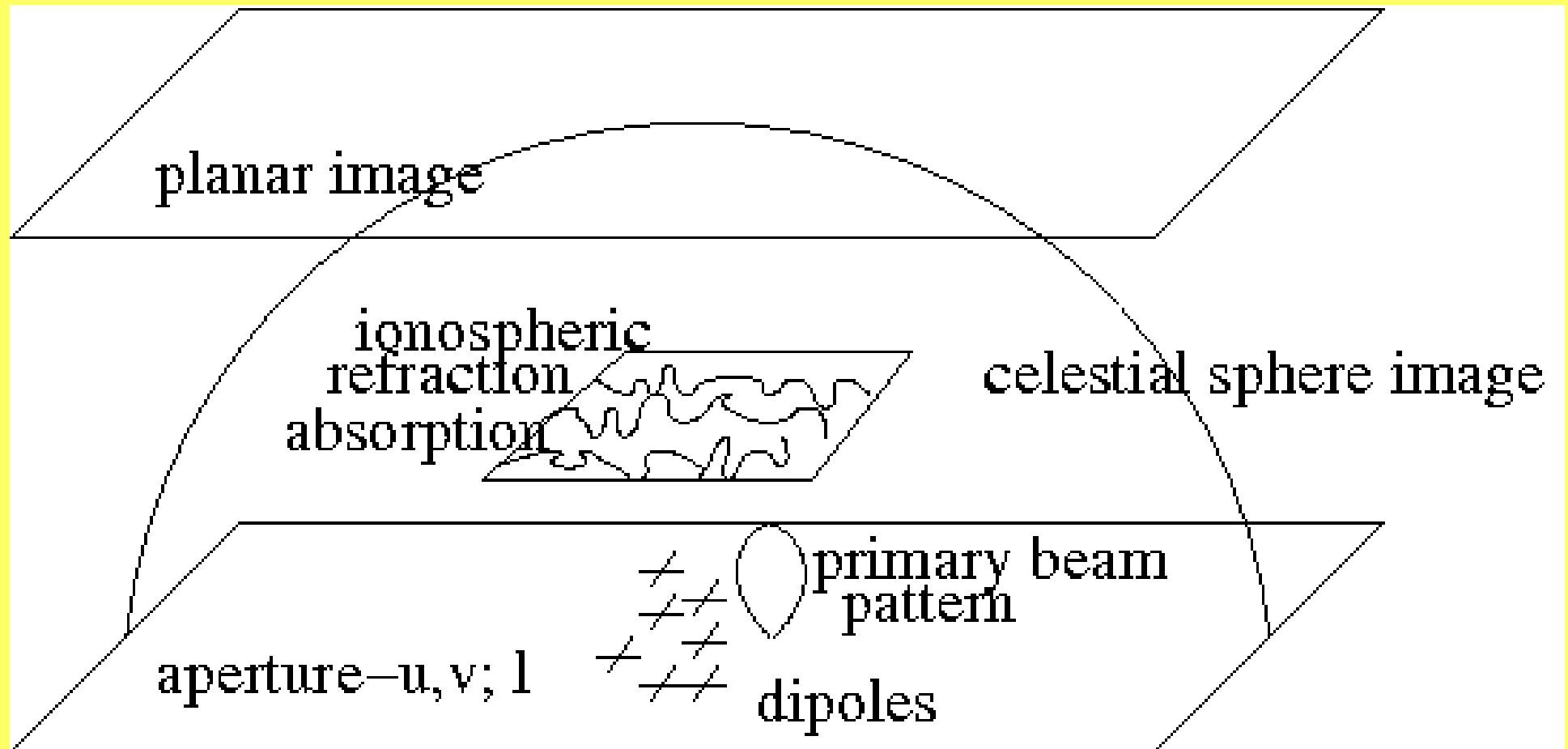
PAPER PROGRESS

- Start in 2004
- **NSF funding:** (1) 2005-2006 correlator development grant; (2) 2006-2008 experiment “starter” grant, including WA deployment; (3) other funding via parallel projects (CASPER, FASR) and Carilli MPG award; (4) new 2008-2011 NSF grant.
- **PAPER in Green Bank: PGB.** This has evolved from 2-antenna interferometer in 2004 August to 8-antenna array in 2006; 16-antenna array 2008 May; also, single-antenna test facility.
- **PAPER in Western Australia: PWA.** 4-dipole array deployed: 2007 July.
- **PGB 16-antenna:** 2008 October with revised design.
- **PWA:** 32-dipole in 2009 May; 64-dipole in 2009 Aug.

2007 July – Western Australia
John Richards-lease holder;
Ron Beresford, CSIRO; DB



Ultra Wide Field Imaging



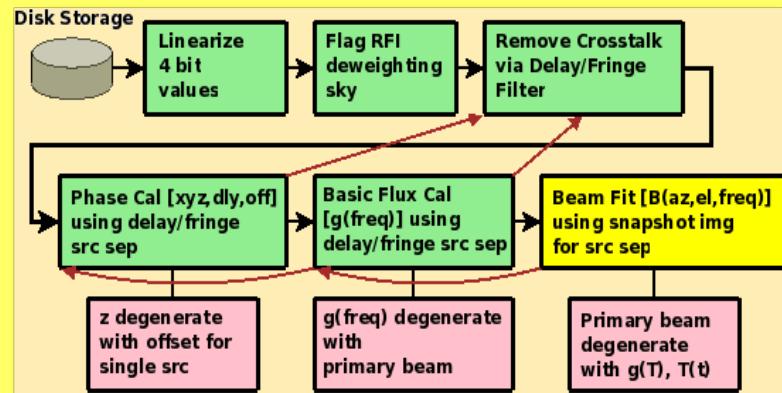
AIPY: Calibration & Imaging – Parsons

Parameter Space:

$$V_{ij}(\nu, t) = \sum_{s=srcts} g_i(\nu) g_j^*(\nu) I_{s,\nu_0} \left(\frac{\nu}{\nu_0} \right)^{\alpha_s} e^{2\pi i (\vec{b}_{ij}(\nu, t) \cdot \hat{s}_s + \nu \tau_{ij} + \phi)}$$

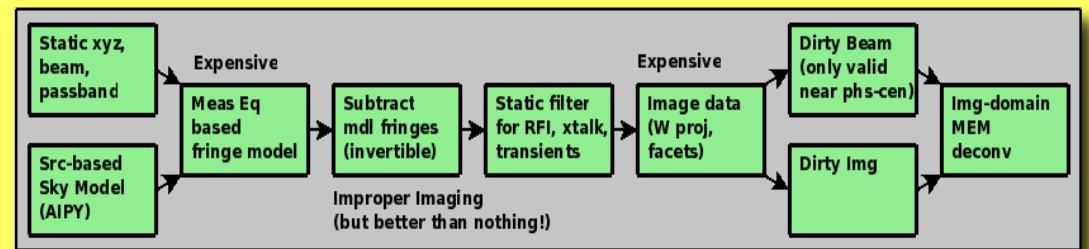
Bootstrap: Direct, fast, imperfect

“Sometimes you can't get started because you can't get started” – Don Backer



- Does not rely (excessively) on priors
- Takes advantage of wide bandwidth
- Addresses degeneracies one at a time

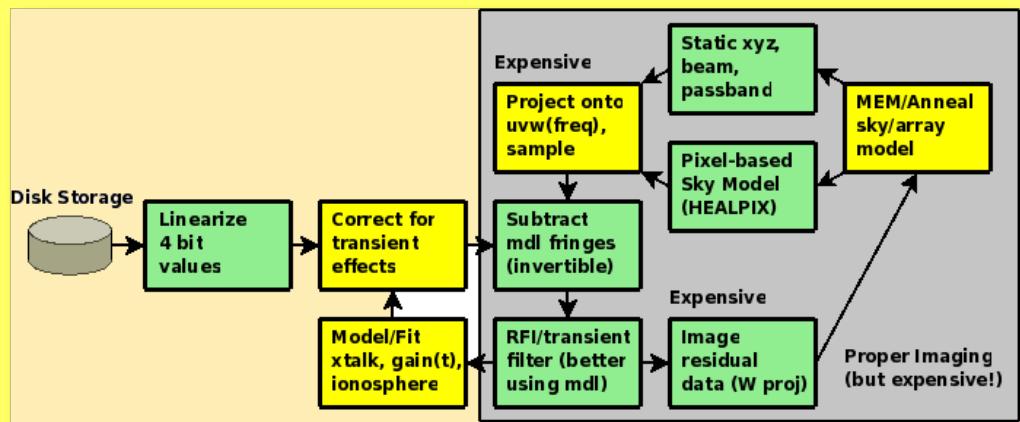
Model-Fit: Clean, correct, expensive



AIPY: Another imaging package? Why?

- Inherently wide-field (native W projection)
 - Large relative bandwidth brings new tools
 - Non-tracking primary beam changes imaging
- Secondary advantages:
- “Be in control of thy tools”
 - In-house expertise
 - Python is modular, object oriented, extendible

- Many parameters are strongly degenerate, requiring simultaneous fitting to tease them apart.
- Proper image deconvolution involves using the full measurement equation.
- Various parameters (ionosphere, gain, xtalk) change on different timescales.
- Huge parameter space, different variance in parameters → simulated annealing?
- If parameter space is not smooth, this is not an easy problem



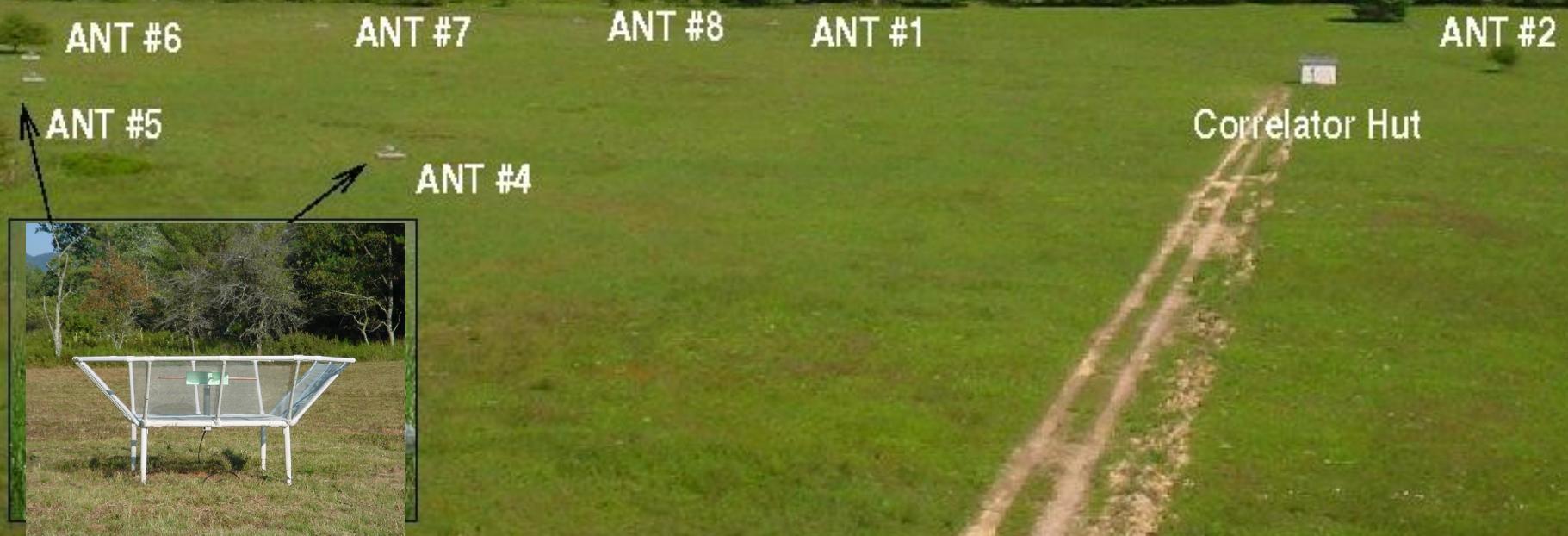
PRECISION ARRAY TO PROBE EPOCH OF REIONIZATION

GALFORD MEADOW -- NRAO: GREEN BANK, WV

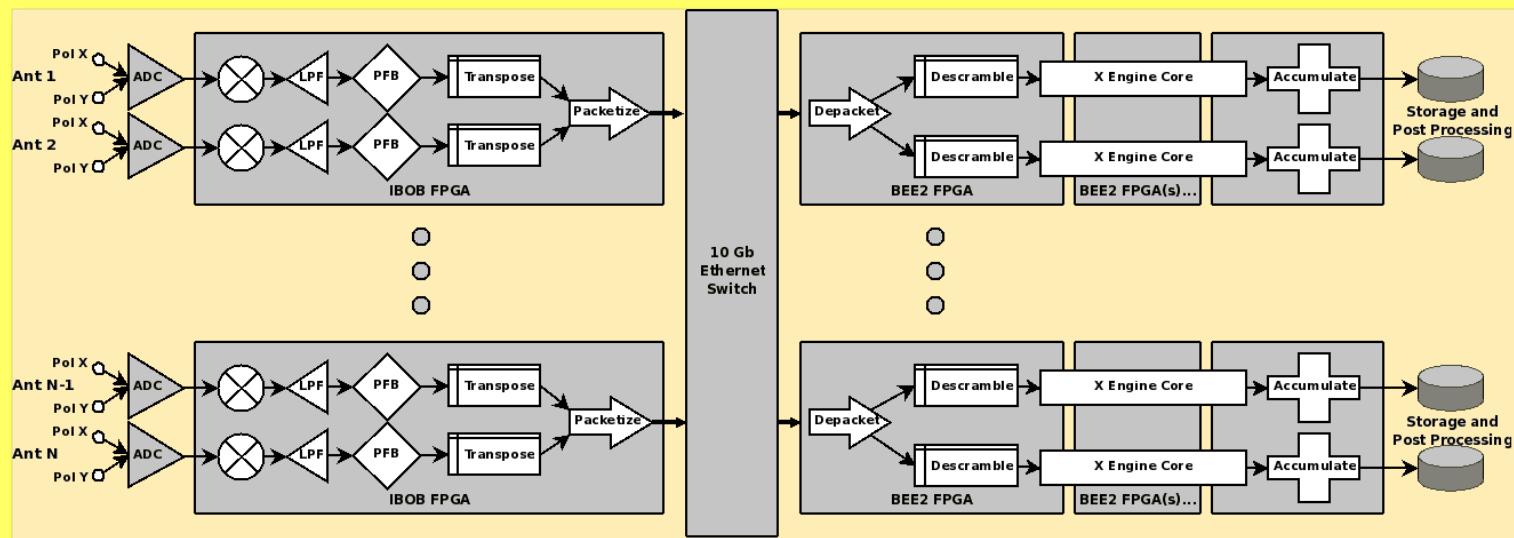
D. Backer, A. Parsons, M. Wright, D. Werthimer (UC Berkeley);

R. Bradley, C. Parashare, N. Gugliucci, E. Mastrantonio, D. Boyd (NRAO, UVA);

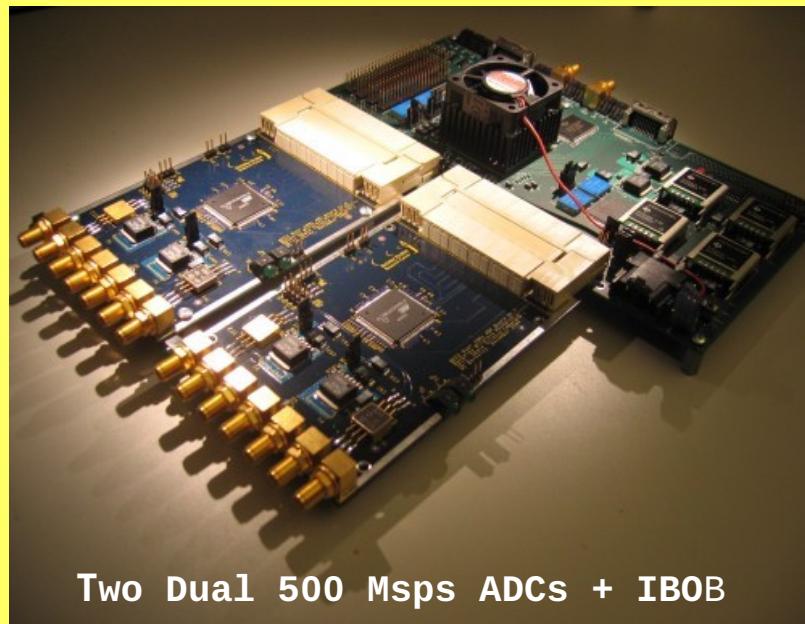
C. Carilli, A. Datta (NRAO/SOC); J. Aguirre (Colorado)



PAPER/CASPER “Packetized” Correlator

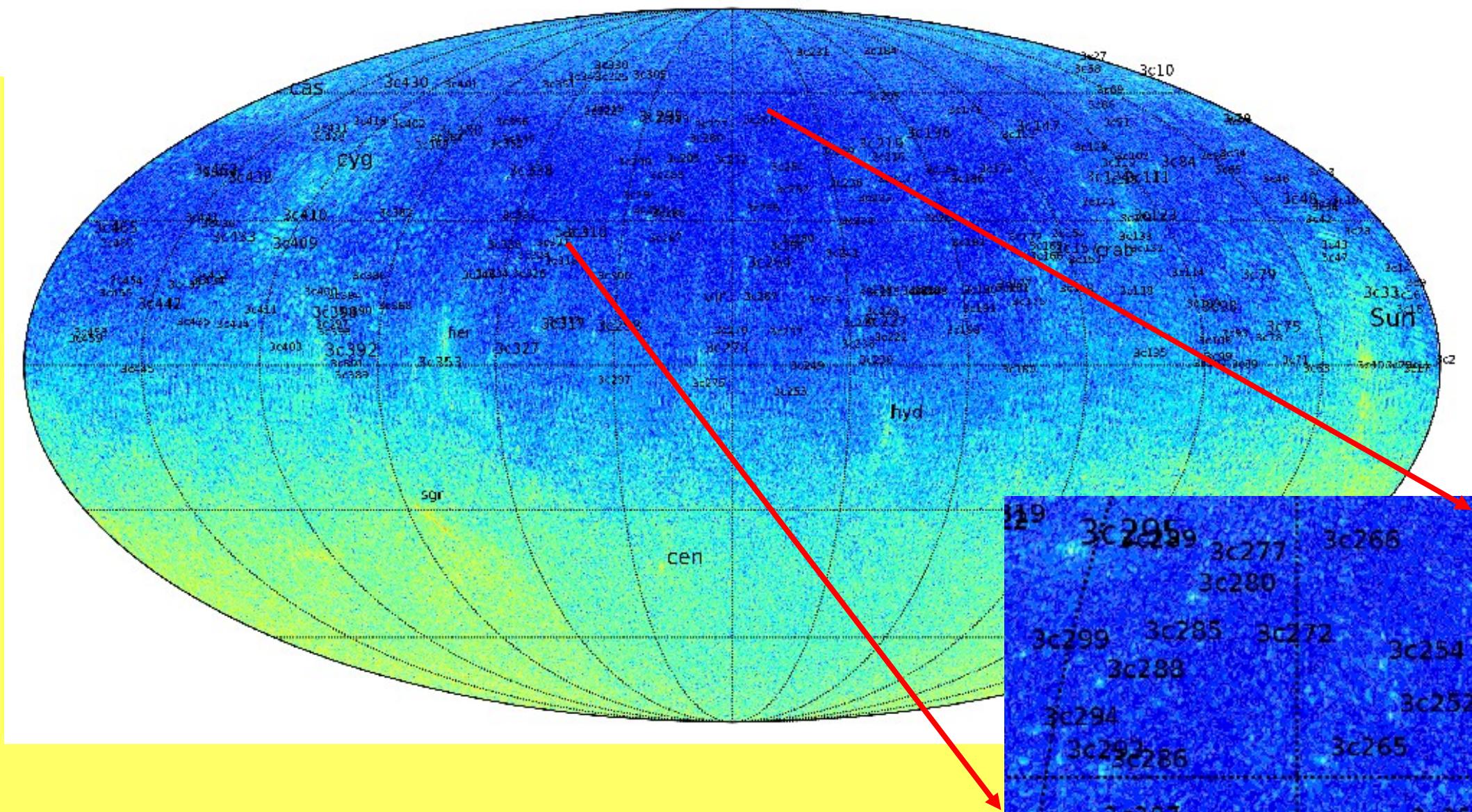


Parsons et al.
2008 PASP, in
press



- 130-170 MHz
 - 8 Dipole
 - 72-hour integration
 - Peak: 10,000 Jy (red)
 - Min: ~100 mJy (blue)

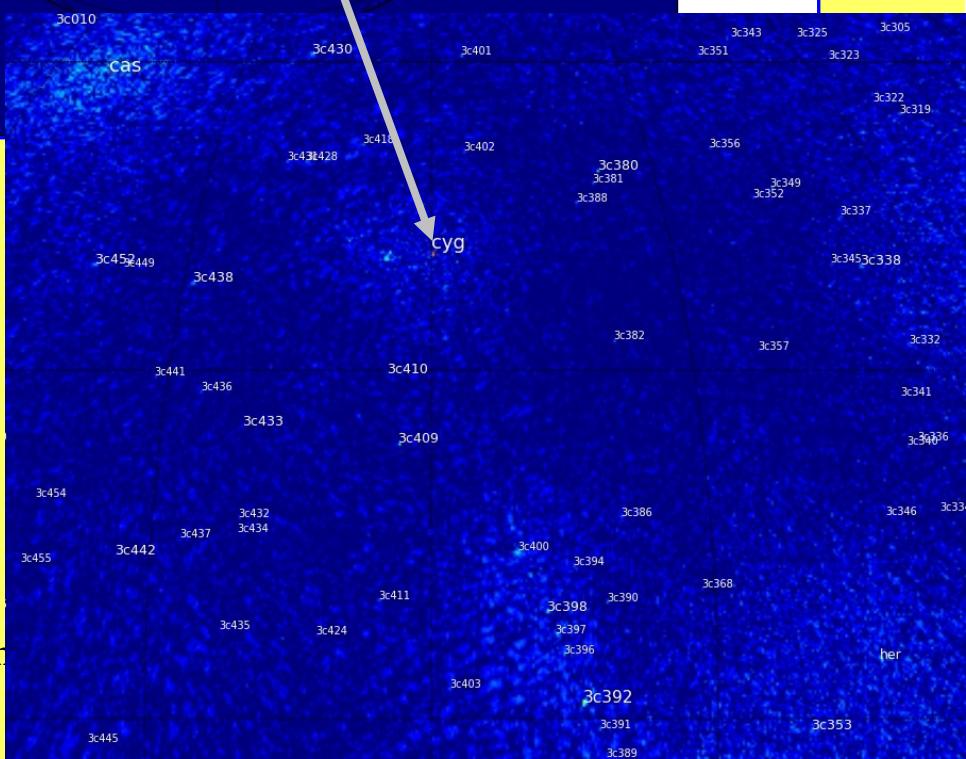
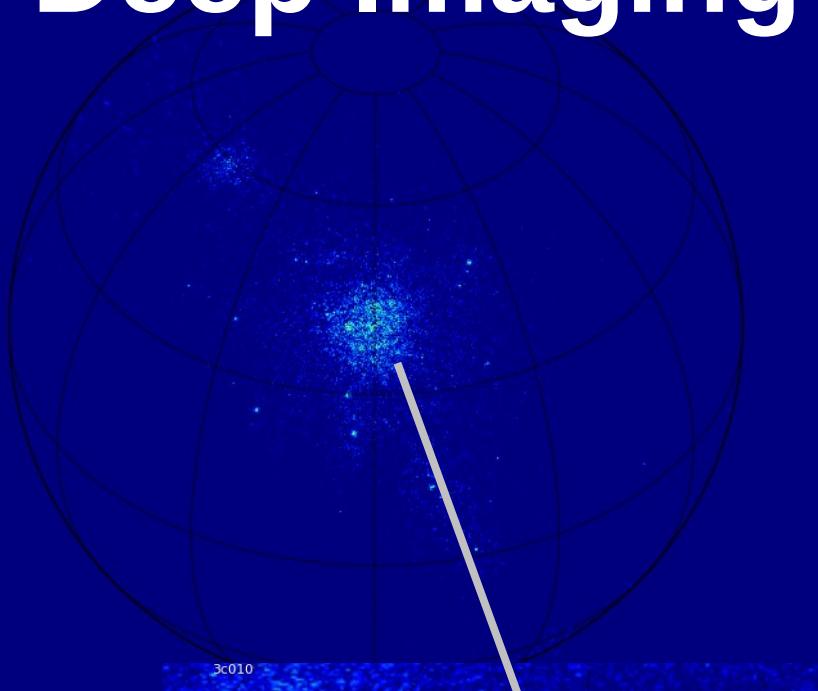
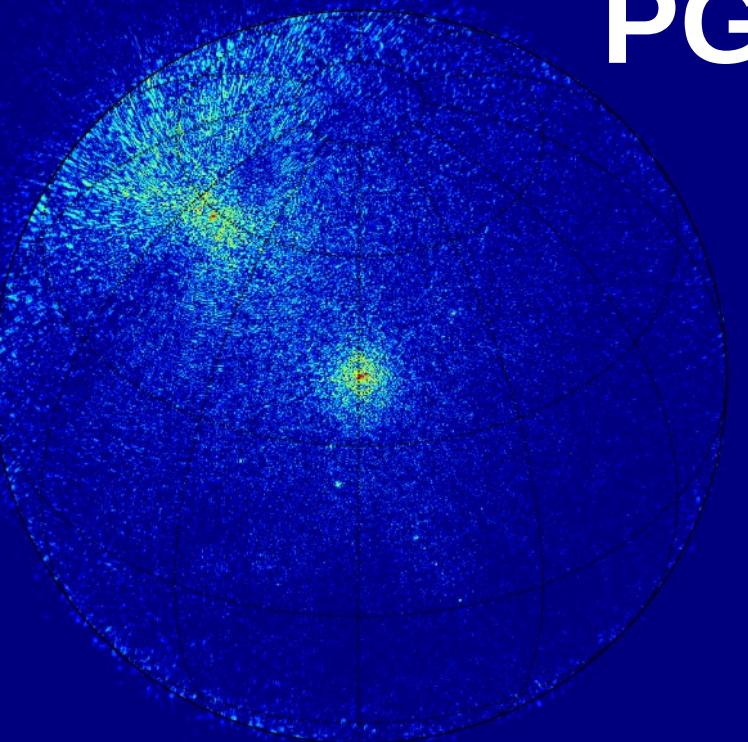
PAPER in Green Bank 2008 Sep



cyg000.bim.fits

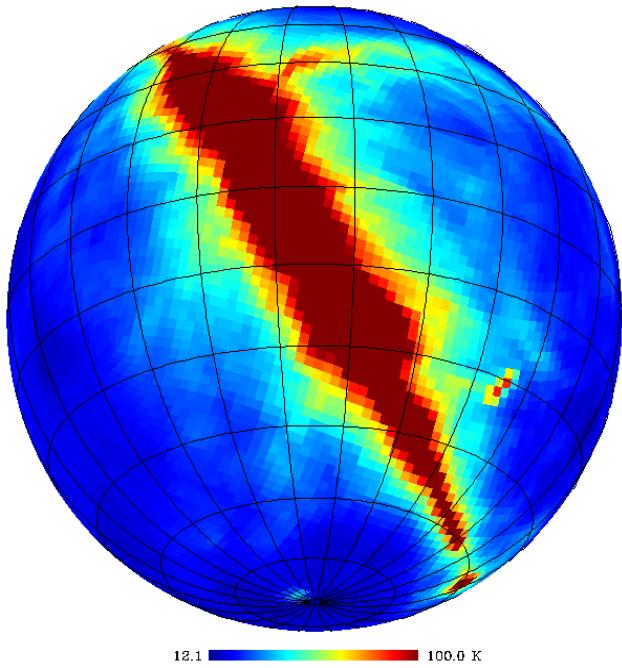
cyg001.bim.fits

PGB: Deep Imaging



- 1 Hour of PGB-16 data:
 - Upper Left – full image on Cyg A center; Cas A too.
 - Upper Right – Cyg/Cas removed leaving “halo”
 - Right – Galactic plane sources modeled

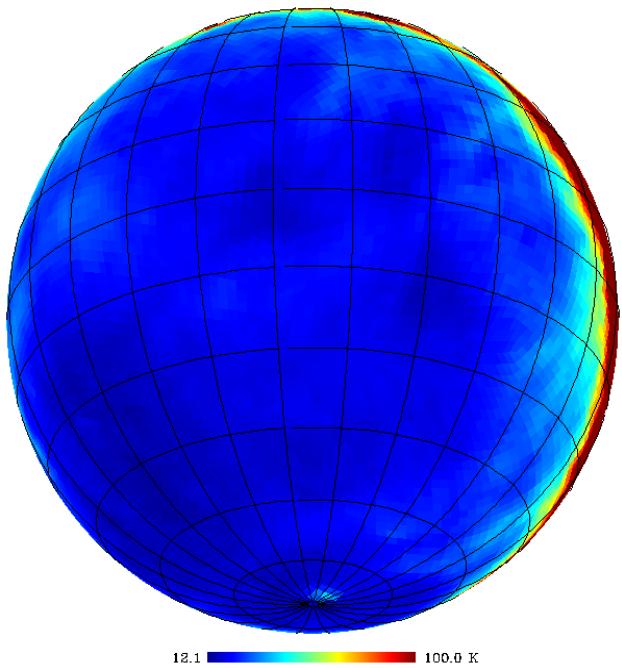
Haslam Sky: Jun



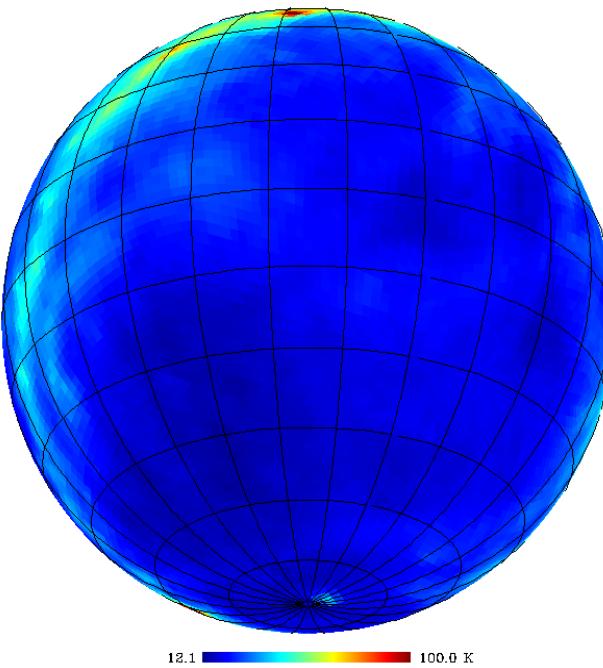
Annual Campaign:

**Galaxy ~beyond horizon at night
when ionosphere is at minimum TECU:
Australian Spring: Sep-Nov (below),
not Winter (e.g., Jun; left)**

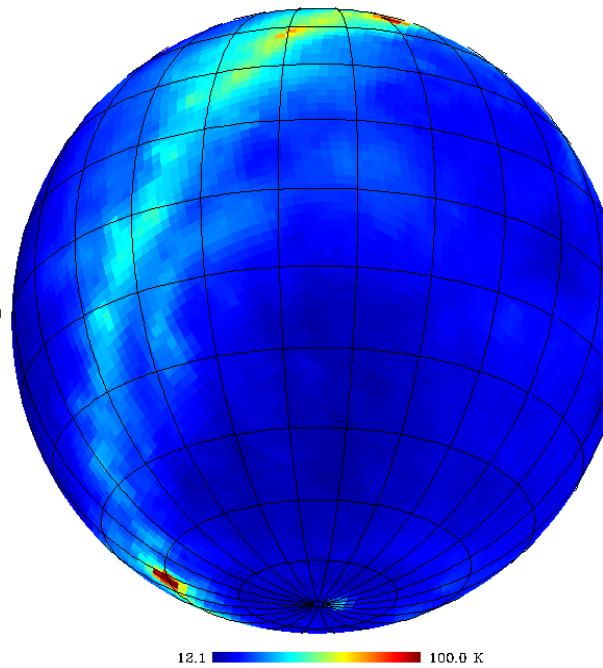
Haslam Sky: Sep



Haslam Sky: Oct



Haslam Sky: Nov



SUMMARY

- *Step by step approach* successful.
- *Green Bank test array* essential.
- *AIPY* and related calibration/imaging progressing rapidly; polarization soon.
- *PWA-64 deployment* 2009 Apr-Aug; 2-3 month integration during 2009 Sep-Nov season of cold synchrotron sky at night.
- *PWA-128 in 2010:* power spectrum detectability dependent on configuration, foreground removal, other systematics.
- *Mid-decade vision:* ~100M USD effort with decision point mid-decade; potential national/international collaboration.

The LOFAR observatory – de Bruyn URSI GA 08aug

Frequency ranges : LBA 10 - 80 MHz and HBA 115 - 240 MHz

2 types of dipole antennas:

- isolated dipoles (LBA)
- tiles (4x4 dipoles, HBA)

Dimensions : 2 km - 100 km - >1000 km

Configuration: NL 36 - 48 stations
Europe ~ 10+ stations

Variable station sizes : 24 - 96 antennas
(not intended: effect of rescope !)

Sensitivity (after 4 h, 4 MHz)

- @ 50 MHz ~ 3 mJy
- @ 150 MHz ~ 0.15 mJy

Up to 8 simultaneous users possible

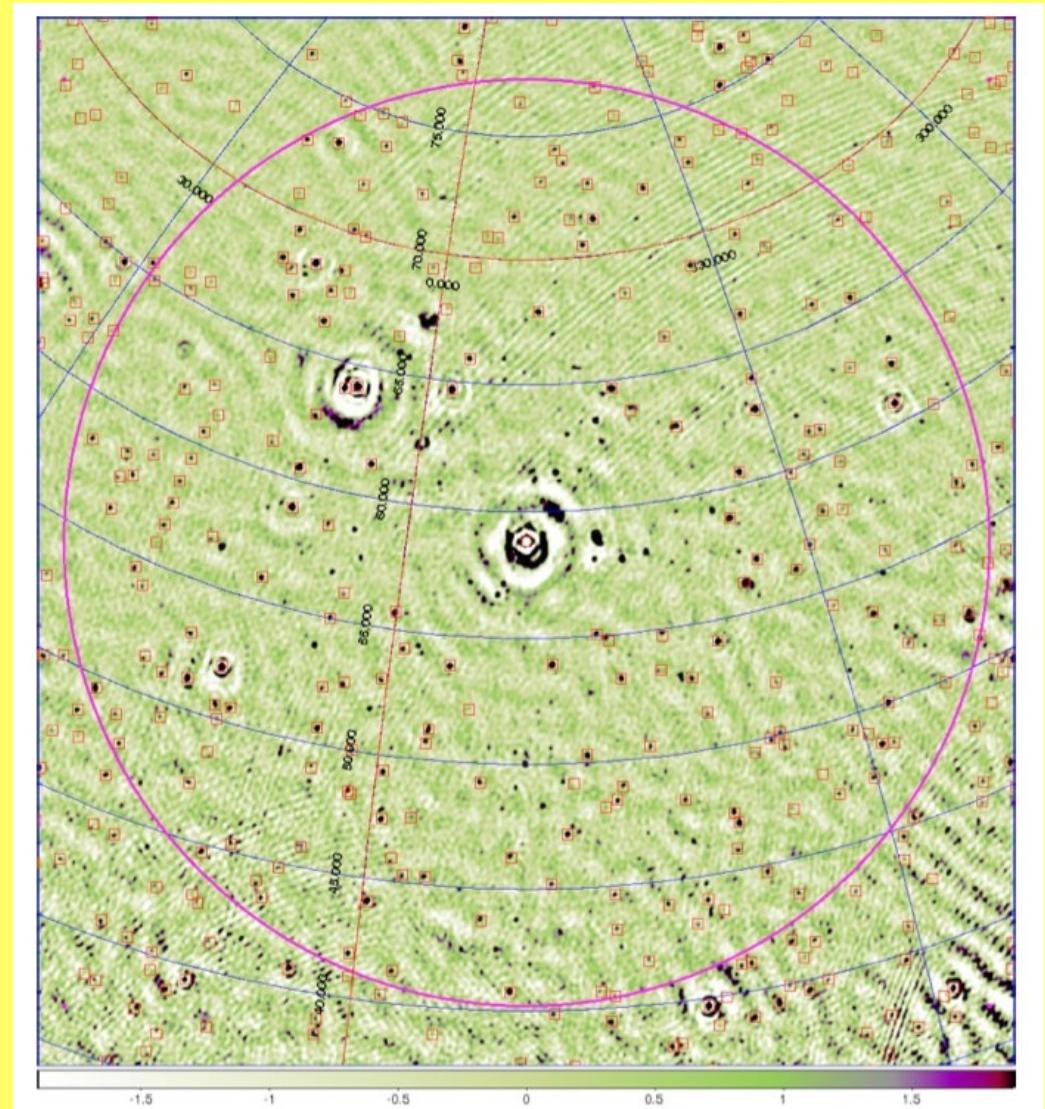


Deep HBA image : 10' PSF , sub-Jy noise

36 subbands:
MFS from 125 - 175 MHz

24h integration using
20 dipoles +
4 tiles (tracking CasA)

tilebeam $\sim 25^\circ$



Roll-out and Planning

Stations:

- Oct 08 2 stations
- Dec 08 4 + 6 ('superstation')
- Apr 09 20 stations + (2 - 7) in Europe

Central processor (BG/L \Rightarrow BG/P transition) Jul08

Off line cluster (5 Tflops) + 500 TB storage Dec08

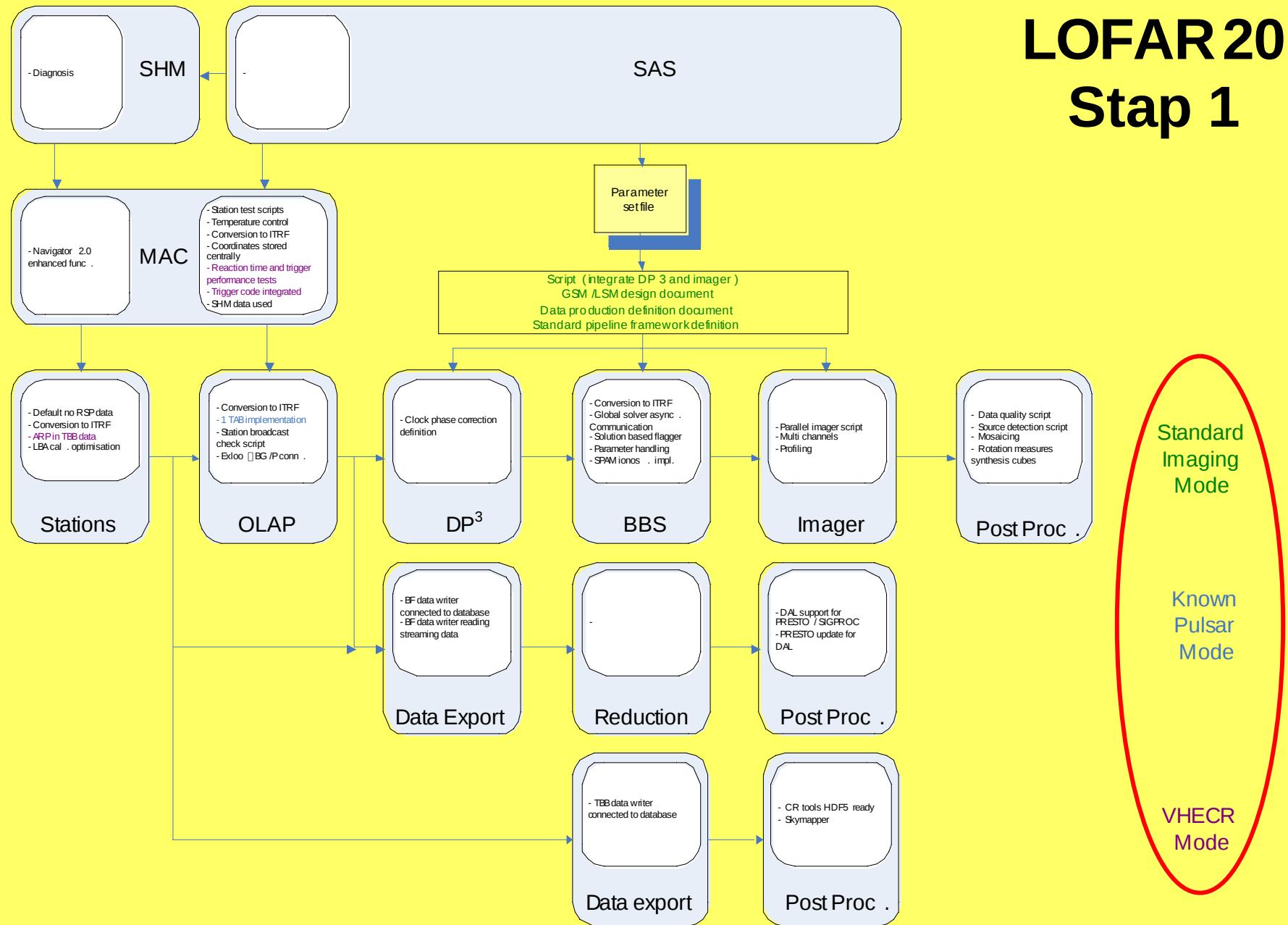
Technical/Software commissioning: Oct08 -Apr09

Software integration: Scheduling / Monitoring / On-line applications /Off-line processing

Construction of a Global Sky Model (GSM): summer 09

LOFAR software components & functionality in late 2008

LOFAR 20 Stap 1



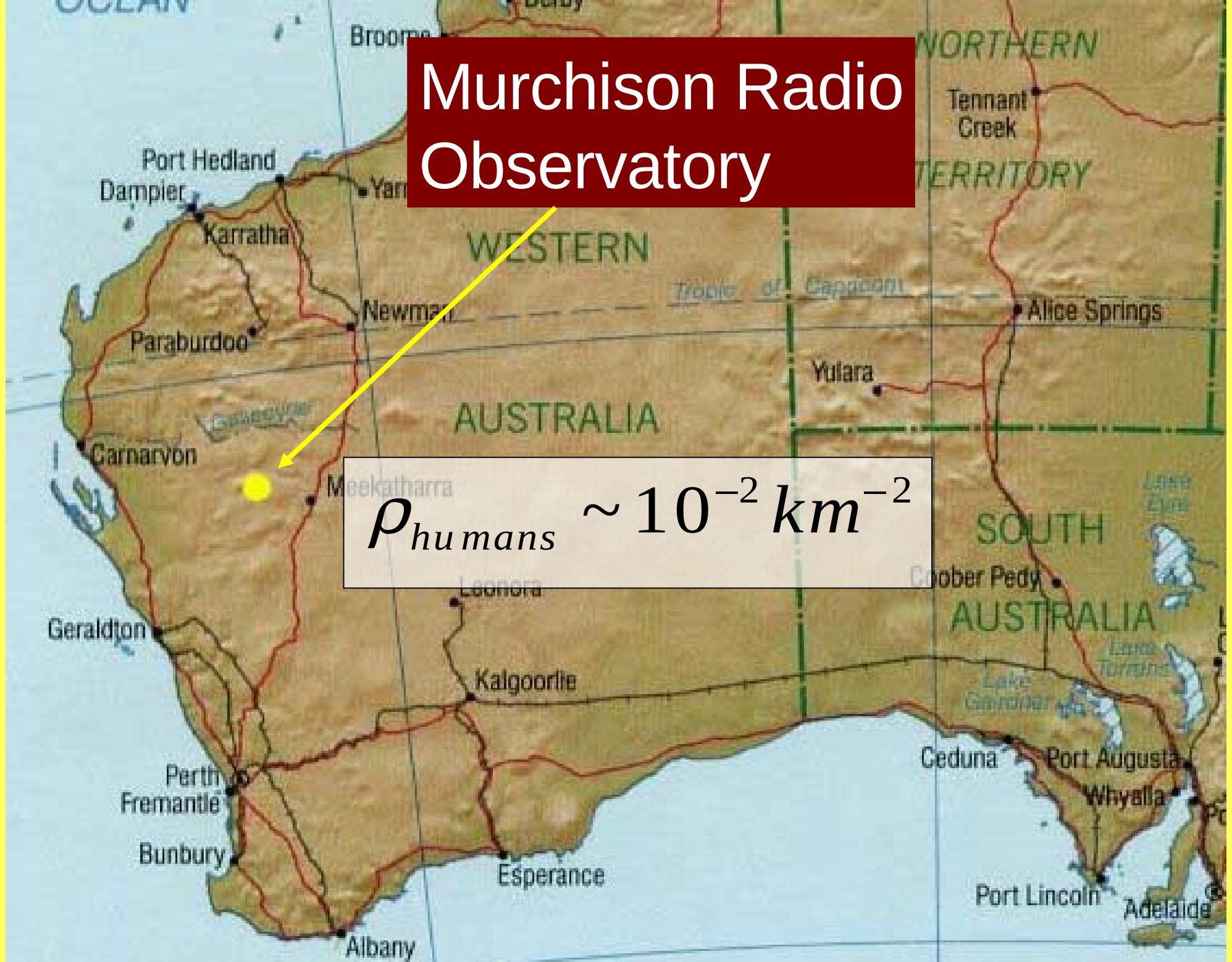
MWA: Murchison Wide-field Array Lonsdale/Greenhill

- A wide-field, low-frequency imaging array
- Optimized for wide FOV, high survey speed
- Frequency range 80-300 MHz
- Three key science goals
 - Epoch of Reionization
 - Solar, Heliospheric and Ionospheric
 - Radio Transients
- Designed to exploit RFI-quiet site in Western Australia

The Partnership

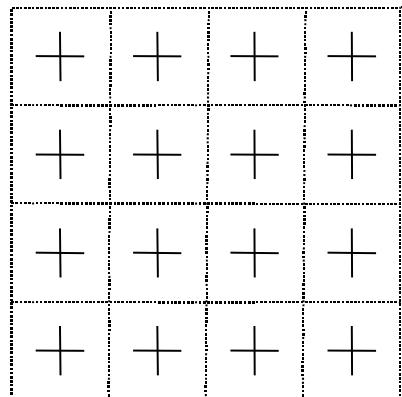
- Massachusetts Institute of Technology
 - Haystack Observatory (Project Office)
 - Kavli Institute
- Harvard SAO
- CSIRO (via synergy with ASKAP)
- UMelbourne, Curtin, ANU (founding partners)
- USydney, UTasmania, UWA, and others, ...
- Raman Research Institute, India
- Government of WA

Murchison Radio Observatory

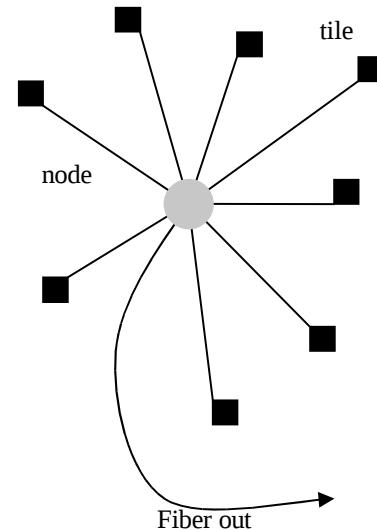


Physical Layout

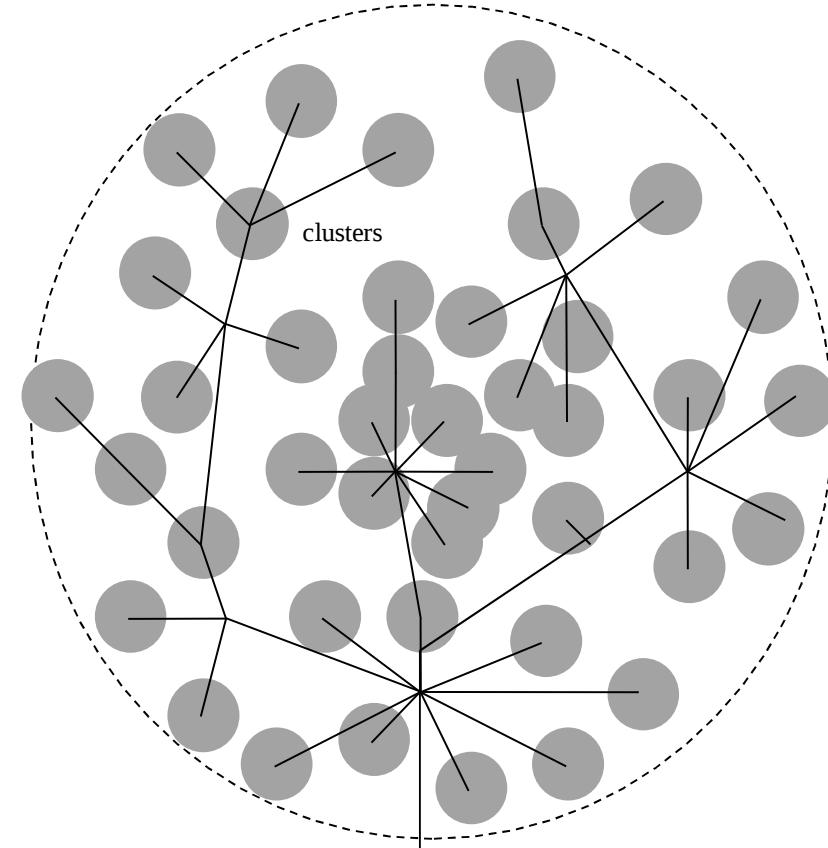
Antenna tile (~4m diam.)



Cluster (50-100m diam.)

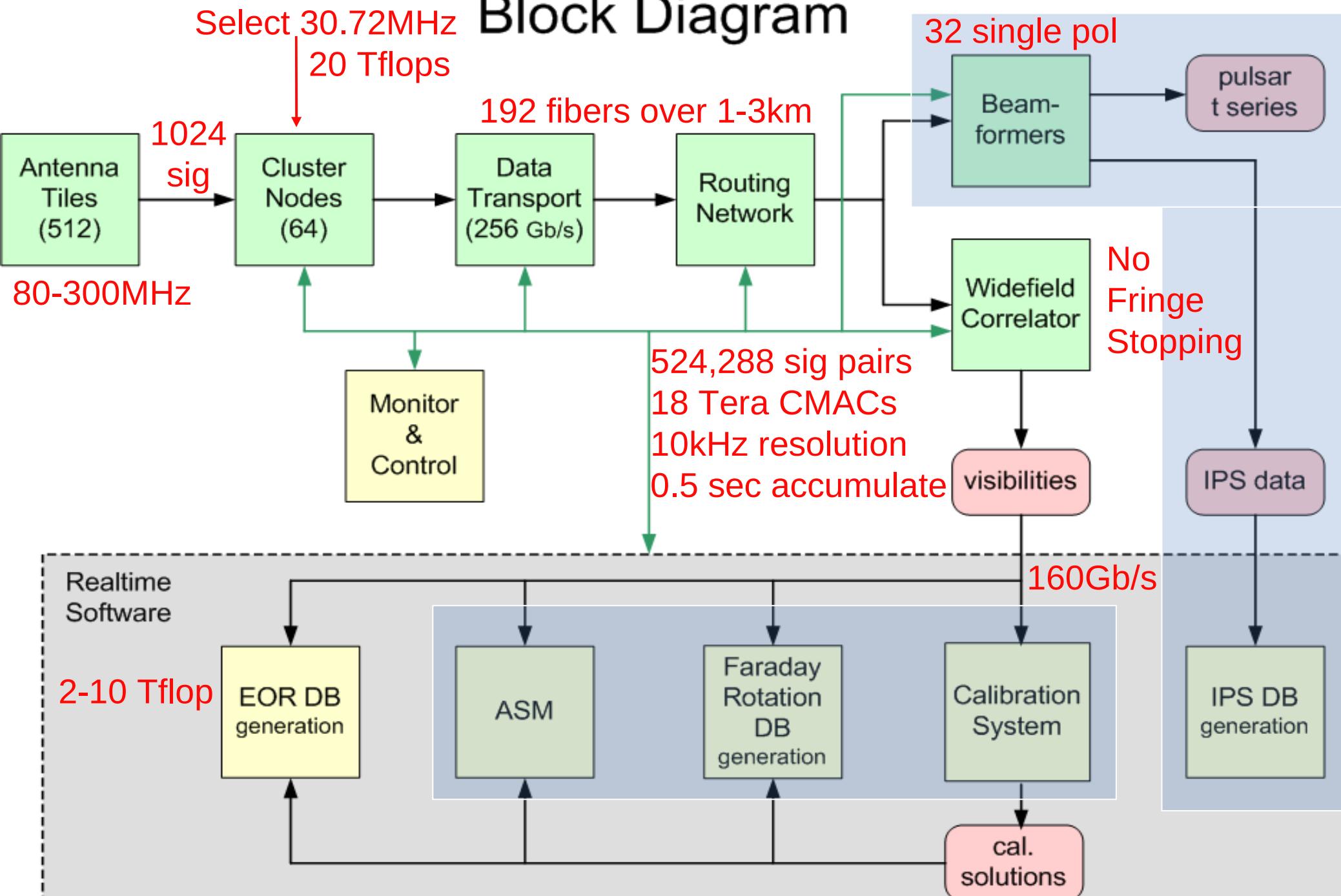


Array (~1.5km diam.)



Central Processing

MWA System Block Diagram



MWA SURVEY

Band 1

84 pointings.

Frequency of 96 MHz

1 x 32 MHz band.

NSIDE 1024

Band 2

213 pointings.

Frequency of 147 MHz

3 x 32 MHz band.

NSIDE 2048

Band 3

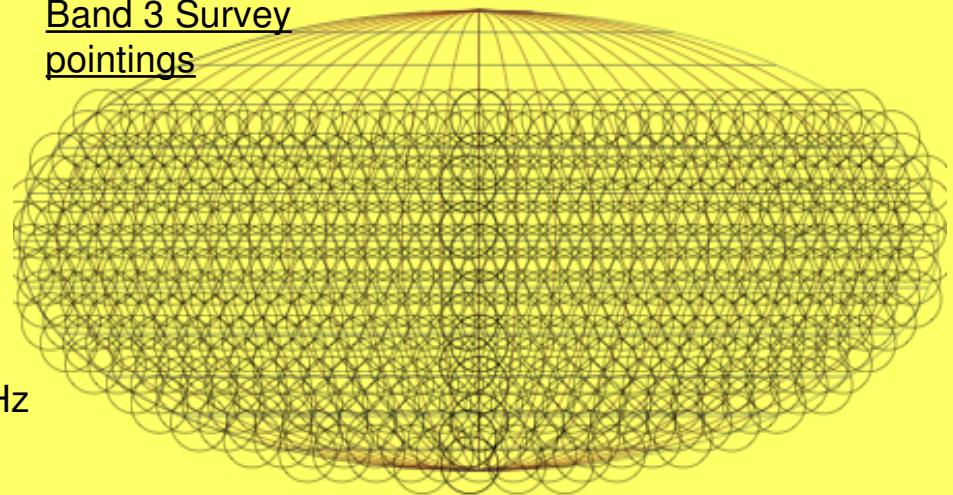
574 pointings.

frequency of 247 MHz

4 x 32 MHz band.

NSIDE 4096

Band 3 Survey
pointings



Imaging the full beam.

60 percent overlap between adjacent beams.

Assuming 16 second slew times and 32 second integration times.

Fields observed at transit.

Total Survey time in seconds:

BAND 1 == 4032 (67 min)

BAND 2 == 30720 (8.5 hours)

BAND 3 == 110272 (1.2 days)

Storage Format:

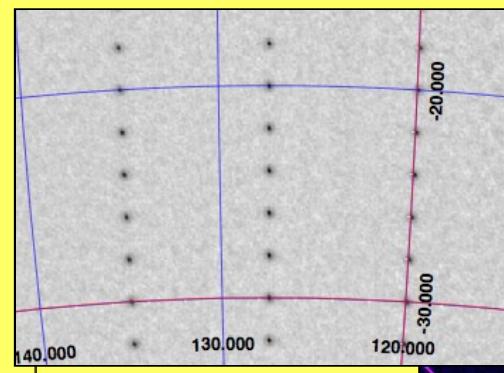
Each integration regridded into HEALPIX for rapid indexing:

Correcting Wide field & Ionospheric distortion.

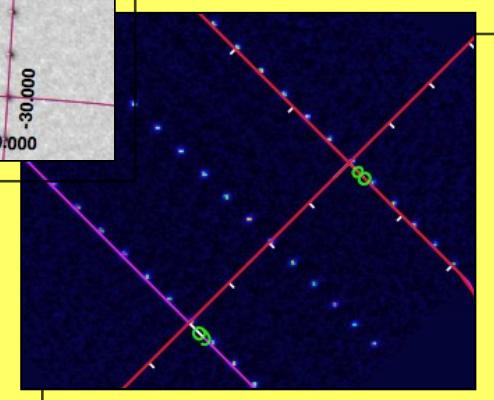
Full Stokes, all-sky south of dec. 40.

Storage requirements a strong function of resolution = 10 \rightarrow 55

Stored as pixelisation but Images presented in HPX



Original l,m map
(above)



HEALPIX image
(HPX)

Sensitivity: Point Source Sensitivity in a single (40 kHz) channel \sim 90 mJy, but classical confusion limit is 800 mJy (@100MHz) and sidelobe confusion limit is comparable. -- Assumes confusion is 1 source per 10 synthesized beams (1 source per beam is \sim 100 mJy)